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Calendering of coextruded polymer structures

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ABSTRACT: The velocity and pressure fields that form within the gap of a calender are calculated with one-dimensional and two-dimensional isothermal monolayer models. The one-dimensional model simplifies the momentum balance and the continuity equation by the lubrication approximation. Pressure and velocity fields are obtained analytically with this calculation. The velocity and pressure fields are numerically calculated with a two-dimensional model based on Forge®2005. Forge®2005 is based on a Finite Element Method. The pressure field is determined by the gap height, the circumferential speed of the rolls and the rheological behaviour of the polymer. The one and two-dimensional pressure fields are compared.

Key words: gap, calender bank, lubrication approximation, Finite Element Method

1 INTRODUCTION

Coextruded polymer structures widely used in the packaging industry are usually produced by calendering. Figure 1 shows a typical coextruded film. The binder (a grafted polypropylene) is in-between polyamide and polypropylene layers.

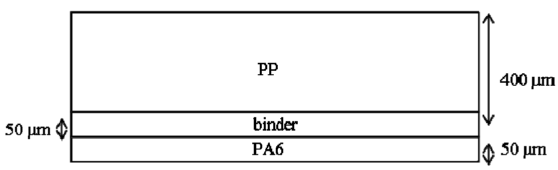

Fig. 1. The multilayer structure

Figure 2 schematically shows a calender line. The different polymers are first melted in separated extruders and then forced, through a feed block, in a single sheet die whose aim is to deliver at die exit a multilayer film with a uniform thickness distribution for each layer. This multilayer film is then stretched on a short distance at a low draw ratio and then calendered between two cooled rotating rolls. Eventually, the film is wound up.
The objective is to obtain a final product with good aspect and satisfying adhesion properties as well as a uniform thickness distribution. The thickness distribution is governed by the die flow. The surface finish is developed mostly during the calendering step. Adhesion properties seem to be influenced by the successive steps of the process: the die flow, the stretch between die and calender, but also the flow in the calender.

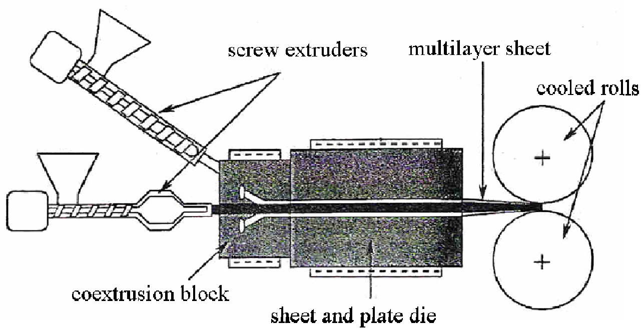

Fig. 2. A calender line

Processing parameters during the calendering step are numerous: the flow rates and temperatures of the different layers delivered by the extruders, the temperature (T_1, T_2) and the rotation velocity (Ω) of the rolls, the gap between the two rolls ($2h_0$) but also the size of the bank (the reservoir) of polymer upstream the roll nip (2H). Figure 3 shows the calender flow configuration.

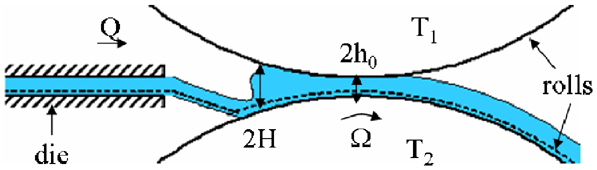

Fig. 3. Calender flow configuration

Adhesion seems to be a subtle function of all these calendering parameters. For this reason, it is necessary to develop a non-isothermal multilayer thermomechanical model for the calendering step.

2 BIBLIOGRAPHIC REVIEW

The calendering process has been widely studied in the seventies [1,2,3,4,5], but especially in the case of polyvinyl chloride (PVC) with a very important bank ($H/h_0>20$) [2], and with a roll temperature which was near the PVC inlet temperature (nearly isothermal conditions) [5].

Early models are based on the so called lubrication approximation [1,2,3,4,5] using Newtonian or viscoplastic shear thinning behaviour.

First, assuming that there is no flow parallel to the roll axis, two-dimensional monolayer finite element models have been developed [6,7]. Then, with a three-dimensional monolayer finite element model, Luther has accounted for the widening of the polymer sheet through the calender bank [8].

In two-dimensional isothermal monolayer conditions, Agassant [6] has considered the vortices, shown figure 4, which may occur in an important calender bank. The results obtained for the pressure field are similar to those get with a model based on a symmetrical qualitative analysis. However, the kinematics in the bank is obviously different from the symmetrical analysis and this will influence the interfaces location in multilayer conditions.

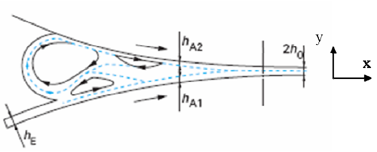

Fig. 4. Flow between the rolls [1]

In two-dimensional non-isothermal conditions, Mitsoulis [7] has computed the temperature field which is quite different from the one computed with the lubrication approximation.

Our objective is to develop a model accounting for the small banks encountered in the process, for multilayer structures and for highly non-isothermal conditions (the temperature of the different polymers emerging from the die is up to 200°C while the roll temperature is below the crystallisation temperature of each polymer).

In this paper, we consider only one layer, we assume isothermal conditions and we account for small banks as shown figure 3. We develop a two-dimensional finite element model and we compare the results to the lubrication approximation theory.

3 PURELY VISCOUS ISOTHERMAL MODELS

3.1 Early models [1]

The early models are based on the qualitative analysis shown figure 5. It is based on the lubrication approximation and the mechanisms linked to hydrodynamic pads. Moreover, in this analysis, the flow between the rolls is supposed to be symmetrical. Indeed, it is supposed that diameter and velocity of the two rolls are the same. Especially, the non-symmetrical phenomena shown figure 4 are neglected and become symmetrical.

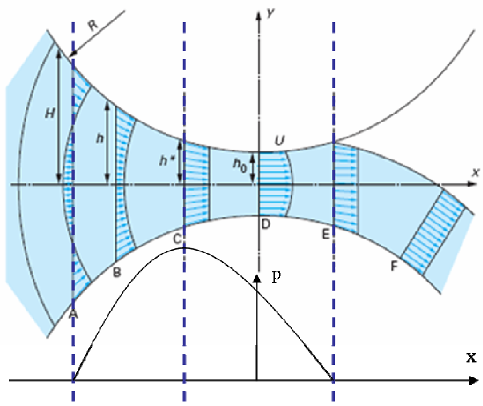

Fig. 5. Kinematical flow in the calender nip and pressure distribution [1]

Eventually, in this qualitative analysis, the polymer melt sticks to the top roll and is conveyed into the direction of the minimum gap. Upstream this minimum gap (at point C in figure 5), the velocity profile is flat, the mean velocity equals the circumferential speed of the rolls and the pressure is a maximum. This two-dimensional qualitative analysis shows a pressure profile and a thickness ratio $r=h^*/h_0$. $2h^*$ is the final thickness of the sheet. The material leaves the contact at point E where the thickness is $2h^*$, and the maximum pressure is reached at point C where the thickness is $2h^*$ too (figure 5).

This isothermal one-dimensional model considers a monolayer structure and a sticking contact. The circumferential speed rolls is U. Mass and inertia forces are neglected regarding viscosity forces. The rheological behavior is assumed to be described by the power law.

This model leads to the generalised Reynolds equation (1). Integrating this equation along the contact and assuming that the pressure is zero at the bank entrance (point A) and at point E where the sheet leaves the contact, allows to compute the pressure distribution (2). To get it, we have to know h_0, R, U, K, m and H/h_0 or h_0, R, U, K, m and h^*/h_0.

$$\frac{dp}{dx} = K\left[\left(\frac{2n+1}{n}\right)U\right]^n \frac{\left|h-h^*\right|^{n-1}\left(h-h^*\right)}{h^{2n+1}} \qquad (1)$$

$$P(a) = K\sqrt{\frac{2R}{h_0}}\left(\frac{2m+1}{m}\frac{U}{h_0}\right)\int_{-a_H}^{a}\frac{\left|a^2-a^{*2}\right|^{m-1}(a^2-a^{*2})}{(1+a^2)^{2m+1}}da \qquad (2)$$

with $a^* = \sqrt{\frac{h^*}{h_0}-1} = \frac{x^*}{\sqrt{2Rh_0}}$ and $a_H = -\sqrt{\frac{H}{h_0}-1} = \frac{x_A}{\sqrt{2Rh_0}}$

This one-dimensional model is a good tool to get pressure field but it cannot account for non-symmetrical feeding of the gap shown in figure 3, highly non-isothermal conditions, and coextruded structures.

3.2 *Numerical approach*

We propose an isothermal two-dimensional monolayer model using Forge®2005 finite element method [9]. The rheological behavior is again described by a power law, and the sticking contact is insured using a friction law with a very high friction coefficient. Figure 6 shows schematically the initial geometry. In the calculation, we need several tools to represent the rolls and the die. To get the results, d, h_i, h_0, R, U, K and m has to be known. It is not necessary, as previously to know H/h_0 or $r=h^*/h_0$. They result from the computation. Figure 7 shows schematically the geometry of the flow get during the calculation.

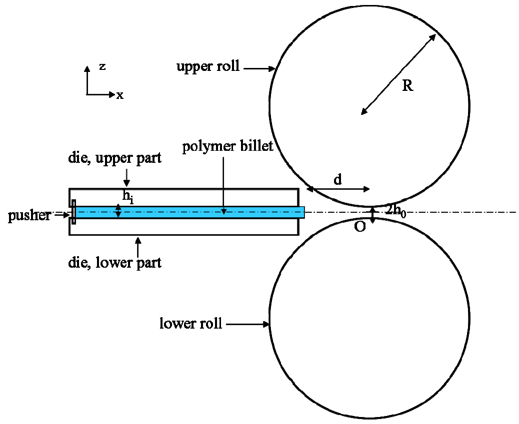

Fig. 6. Initial geometry of the calculation, for the tools and the material

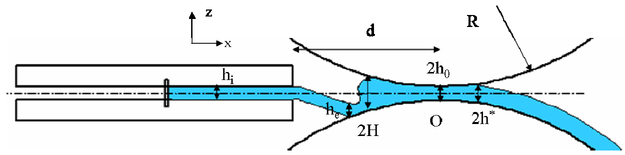

Fig. 7. Final geometry

4 RESULTS

4.1 *Early models*

The final thickness of the sheet is higher than the minimum gap between the two rolls. It depends on the rotation velocity of the rolls, on the rheology of the polymer but also on the importance of the bank, and this is a difficult point because the size of the bank is difficult to control. Figure 8 shows the evolution of r with H/h_0. If we focus on the evolution of p_{max} with several parameters like H/h_0 or h_0, we get the curves shown in figure 9.

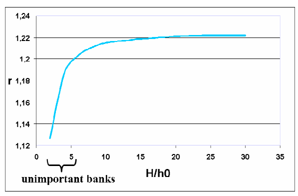

Fig. 8. Spread height r as a function of the bank - h_0=0,25mm; R=125mm ; U=1,5m/min ; K=3000Pa.s^m ; m=0,62

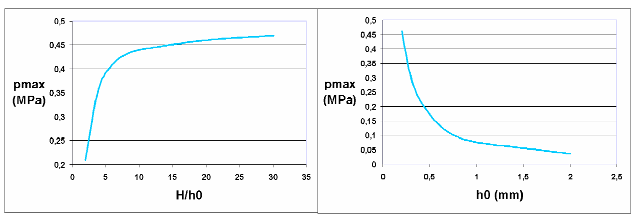

Fig. 9.p_{max} as a function of H/h_0: h_0=0,25mm and h_0: H/h_0=4 - R=125mm ; U=1,5m/min ; K=3000Pa.s^m ; m=0,62

4.2 *Numerical approach*

Figure 10 gives the meshing, the shape of the free surface (the bank) and the pressure field get during the calculation, while figure 11 shows several velocity profiles in the same conditions.

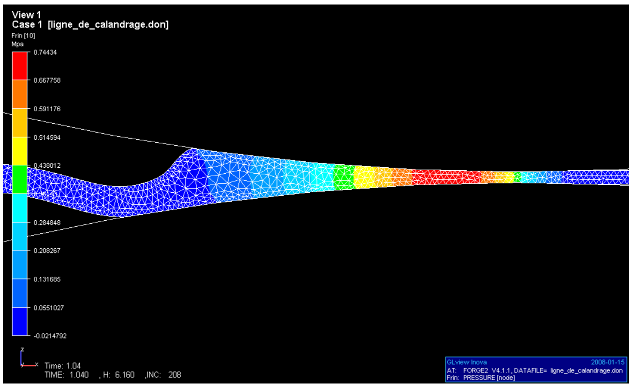

Fig. 10. Meshing and pressure field – h_i=2mm; h_0=0,8mm ; R=170mm ; U=3,3m/min ; K=3000Pa.s^m ; m=0,62

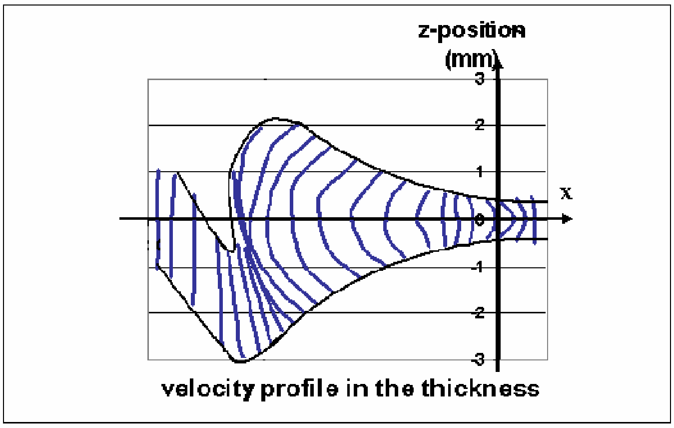

Fig. 11. Velocity profiles in the thickness of the flow for several positions along the x-axis

It is clear that the flow is symmetrical around the gap, but this is no more true at the calendar inlet.

4.3 *Comparison*

Figure 12 shows the pressure fields get with the lubrication approximation and Forge®2005. We observe that pressure fields computed with the two methods are of the same order of magnitude even not equivalent. This may be related to the velocity field at the flow inlet which is quite different when considering the real flow configuration.

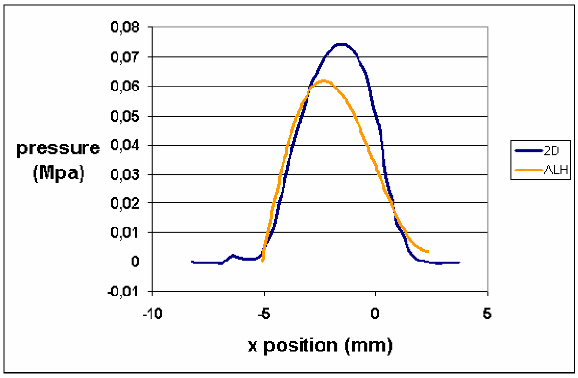

Fig. 12. Pressure fields – h_i=0,85mm; h_0=0,8mm ; R=170mm ; U=3,3m/min ; K=476Pa.s^m ; m=1

5 CONCLUSIONS

For further developments, we will introduce successively non-isothermal effects and coextrusion conditions. Then it will be possible to relate adhesion properties to the thermomechanical parameters of the calendering process.

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